7.0 Breadth Analysis – Constructability

7.1 Raw Material Quantities

The simplest test of an alternative structural system is to quantify the basic materials necessary for construction and compare the values with the existing system. Streamlining the braced frame system involved the removal of four braced frames and the alteration of three others. Material savings were calculated to be nearly ten tons steel HSS-shapes using Excel (Figure 7.1.1).

Steel Savings

Frame	HSS Brace Size	Total Length (ft)	lb/ft	Weight (lb)
3	10x10x$^{1}/_{2}$	(104.9)		
	7x7x$^{1}/_{2}$	34.4		
	6x6x$^{1}/_{2}$	70.5		
4	8x8x$^{1}/_{2}$	68.8		
	7x7x$^{1}/_{2}$	34.4		
	6x6x$^{1}/_{2}$	36.1		
5	8x8x$^{1}/_{2}$	68.8		
	6x6x$^{1}/_{2}$	70.5		
7	10x10x$^{1}/_{2}$	(7.4)		
	8x8x$^{1}/_{2}$	(41.3)		
	7x7x$^{1}/_{2}$	82.6		
	6x6x$^{1}/_{2}$	(42.7)		
8	10x10x$^{1}/_{2}$	(104.9)		
	8x8x$^{1}/_{2}$	34.4		
	7x7x$^{1}/_{2}$	34.4		
	6x6x$^{1}/_{2}$	36.1		
9	7x7x$^{1}/_{2}$	34.4		
	6x6x$^{1}/_{2}$	104.9		
10	7x7x$^{1}/_{2}$	34.4		
	6x6x$^{1}/_{2}$	104.9		
Total	10x10x$^{1}/_{2}$	(217.2)	62.3	(13530.9)
	8x8x$^{1}/_{2}$	130.8	48.7	6368.3
	7x7x$^{1}/_{2}$	220.2	41.9	9226.3
	6x6x$^{1}/_{2}$	380.1	35.1	13342.3
	Weight Savings (tons of steel)			7.70

Figure 7.1.1 Steel Savings for Updated Braced Frame System

Designing a new foundation system greatly reduced the amount of concrete and reinforcing steel needed for construction. The building materials for existing spread-footing system for the braced frames are quantified in Figure 7.1.2. The building materials for the new drilled pier system for the braced frames are quantified in Figure 7.1.3 for comparison. In an attempt to make a fair comparison, I increased the spread-footing materials by 25% and the drilled pier materials by 50% to account for the relative uncertainty of the drilling conditions. Basically, the new system represents a 38% concrete savings and a 24% rebar savings over the existing system. The other fifty column spread footings were tallied and their concrete volumes summed to get the "OTHER" values in Figure 7.1.2. In order to quantify materials, the drilled piers for the other columns were designed to support a typical 250 kilo-pound load. The "other" column footings are not as massive as the braced frame footings; therefore the material savings were not as dramatic. In fact, other columns footings accounted for only sixteen of the four hundred cubic yards of concrete that could be saved by employing a drilled pier foundation system.

note: frame 7 & 8 share a column

Frame	Dimensions			Total Concrete Volume (yd^3)	Steel Reinforcing (ft^3)
	Width	Length	Depth		
1	17	38	4	95.7	17.95
2	17	38	4	95.7	17.95
3	14	14	3	21.8	3.88
4	16	38	3	67.6	16.41
5	16	38	3	67.6	16.41
6	16	16	3	28.4	6.05
7	16	16	3	28.4	6.05
8	16	38	3	67.6	16.41
9	14	14	3	21.8	3.88
10	16	38	3	67.6	16.41
OTHER	*50 Ftgs. of Varying Size*			277.9	67.52
			TOTALS	**839.9**	**188.9**
			+ 25%	**1049.9**	**236.1**

Figure 7.1.2 Building Materials for Existing Spread Footings

note: 2 piers per frame (except 7 & 8 b/c they share a column)

Frame	Approx. Shaft Length Above Rock (ft)	Shaft Depth Into Rock, L (ft)	Diameter of Shaft, D_s (ft)	Total Concrete Volume (yd^3)	Minimum Reinforcing (cu. ft.)
1	25	10	3	18.3	4.95
2	15	10	3	13.1	3.53
3	15	15	4	27.9	7.54
4	10	10	3	10.5	2.83
5	15	10	3	13.1	3.53
6	10	15	4	23.3	6.28
7	10	15	4	23.3	6.28
8	10	15	4	23.3	6.28
9	20	10	3	15.7	4.24
10	20	10	3	15.7	4.24
OTHER	*15*	*5*	3	261.8	70.69
			TOTALS	**434.3**	**120.40**
			+ 50%	**651.4**	**180.60**

Figure 7.1.3 Building Materials for New Drilled Piers

7.2 Cost Impact

The material savings are great statistics, but ultimately the potential of the newly designed systems boils down to cost. I used R.S. Means 2006: Heavy Construction Cost Data to approximate the raw material and construction costs for each major activity affected by the two foundation systems. The cost breakdown for the existing spread footing foundation system is tabulated in Figure 7.2.1. For comparison, the cost estimate for the new drilled pier foundation system is tabulated in Figure 7.2.2. A fear of the unknown clearly manifests itself in the cost estimate of the drilled pier system, leading to an estimate that is practically double the estimate for the basic spread footing assembly.

A1010 210 SPREAD FOOTING ASSEMBLY - includes excavation, backfill, forms, all reinforcement, 3000 psi concrete (chute placed), and screed finished

	2006 Bare Costs			Quantity	Total Costs 2006
	Materials	Installation	Total		
Bulk Excavation	*Per Cubic Yard*				
		4.24	4.24	1469.9	6232
Hand Trim	*Per Square Foot*				
		6.57	6.57	9352.0	61443
Compacted Backfill	*Per Cubic Yard*				
		0.79	0.79	630.0	498
Formwork (4 uses)	*Per Square Foot Perimeter*				
	7.80	48.36	56.16	713.0	40042
Reinforcing, f_y = 60 ksi	*Per Ton*				
	5.37	5.94	11.31	21.0	238
Anchor Bolt Templates	*Per Linear Feet*				
	5.52	20.04	25.56	1584.0	40487
Concrete f_c = 3000 psi	*Per Cubic Yard*				
	31.52		31.52	839.9	26475
Place Concrete, chute	*Per Cubic Yard*				
		6	6	839.9	5040
Screed Finish	*Per Square Foot*				
		4.05	4.05	9352.0	37876
		TOTAL			175414
Note: Overhead & Profit Not Included		**TOTAL w/ regional adjustment factor (Lancaster, PA - 0.929)**			**$163,000**

Figure 7.2.1 Cost Estimate for Existing Spread Footing Foundation System

02465 DRILLED CAISSONS - includes excavation, concrete, 50 lbs. reinforcing steel per C.Y.

	2006 Bare Costs				Quantity	Total Costs 2006
	Materials	Labor	Equipment	Total		
Caisson into Stable Soil	*Per Vertical Linear Foot*					
36"	28.50	11.65	27	67.15	960.0	64464
48"	50.50	14.55	34	99.05	80.0	7924
Caisson into Rock	*Per Vertical Linear Foot*					
36"	28.50	191	286	505.50	370.0	187035
48"	50.50	286	430	766.50	105.0	80483
Mobilization (50 miles)	*Per Drilling Rig*					
36"		730	1700	2430	2	4860
48"		995	2075	3070	1	3070
Excess Material Disposal	*Per Cubic Yard*					
2 miles		1.27	2.68	3.95	434.3	1715
			TOTAL			349551
Note: Overhead & Profit Not Included			**TOTAL w/ regional adjustment factor (Lancaster, PA - 0.929)**			**$325,000**

Figure 7.2.2 Cost Estimate for New Drilled Pier Foundation System

The cost estimate for the streamlined lateral force resisting system is not as dramatic, but it does represent a potential savings over the existing system. I used R.S. Means 2006: Heavy Construction Cost Data to approximate the total cost per ton of HSS-shapes, including basic erection costs. Estimating the cost of the connections proved more difficult. The bracing members are slotted and welded to steel plates with fillet welds. The plates are then welded to the wide-flange columns or beams. Typical connection details are illustrated in Figure 7.2.4, which were taken from the structural drawings provided by EYP.

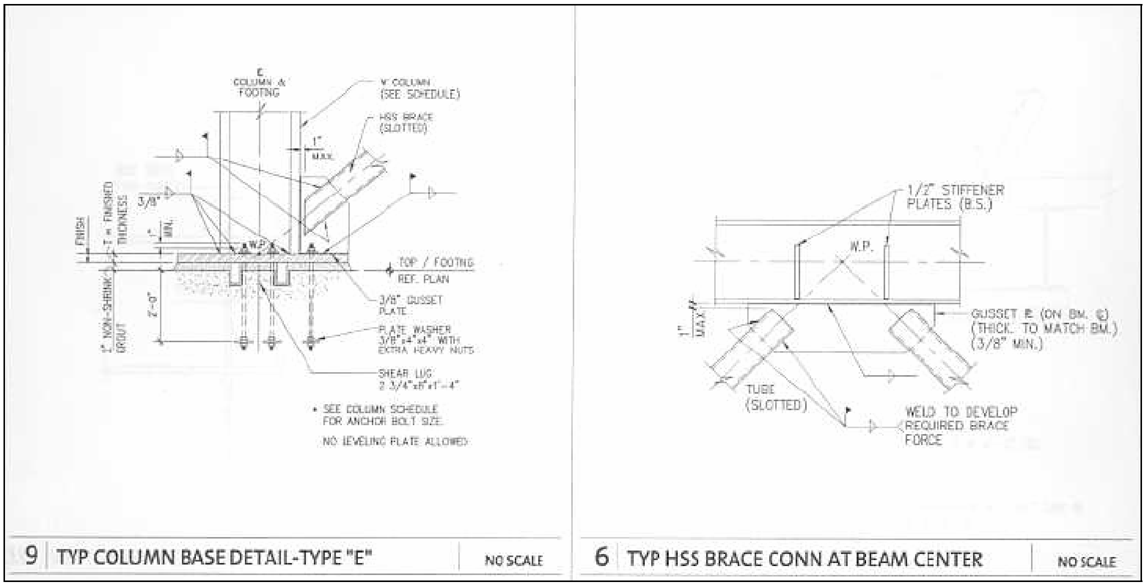

Figure 7.2.4 Typical HSS Bracing Member Connections

Charlie Carter of AISC suggested that an installed fillet weld would cost about $35 per pound of welded metal. I added 10% to that estimate to account for the connection plates. To determine the welding material quantities, I used the tabulated member forces in Figures 4.1.2 and 4.2.2, the basic connection configurations as depicted in Figure 7.2.4, and the minimum weld sizes and lengths as explained in the *Lecture Notes for AE 597E: Design and Analysis of Steel Connections*. Basically, the minimum weld length (L_{weld} >= $4t_{weld}$ with $L_{weld} = {}^{1}/_{4}L_{real}$) controlled the weld size in every connection. The Excel spreadsheets generated in the connection design processes for both the existing and revised systems are available in Appendix C. The connections savings were then added to the steel savings to produce an overall estimate of the money saved by revising the lateral force resisting system. The savings are tabulated below in Figure 7.2.5.

Steel Cost Savings						
	2006 Bare Costs				Quantity	Total Savings
	Materials	Labor	Equipment	Total		
05120 STRUCTURAL STEEL	Per Ton					
Structural Tubing (HSS)	2100.0	43.5	28.5	2172.0	8	16731
WELDED CONNECTIONS	Per Pound					
E70XX 1/4" fillet welds				38.5	43.1	1661
Note: Overhead & Profit Not Included			**TOTAL w/ regional adjustment factor (Lancaster, PA - 0.929)**			**$18,000**

Figure 7.2.5 Savings Estimate for Revising the Lateral Force Resisting System

8.0 Breadth Analysis – Architectural/Mechanical Impact

8.1 Façade Impact

The Vierendeel truss is particularly ingenious for its ability to cooperate with the rectangular openings of the building's façade. The Western façade of the Barshinger Life Science and Philosophy Building is depicted in Figure 8.1.1 with the Vierendeel truss location expressed in light blue. The symmetry of the Colonial Revival-style façade is easily recognizable and should be preserved at all costs.

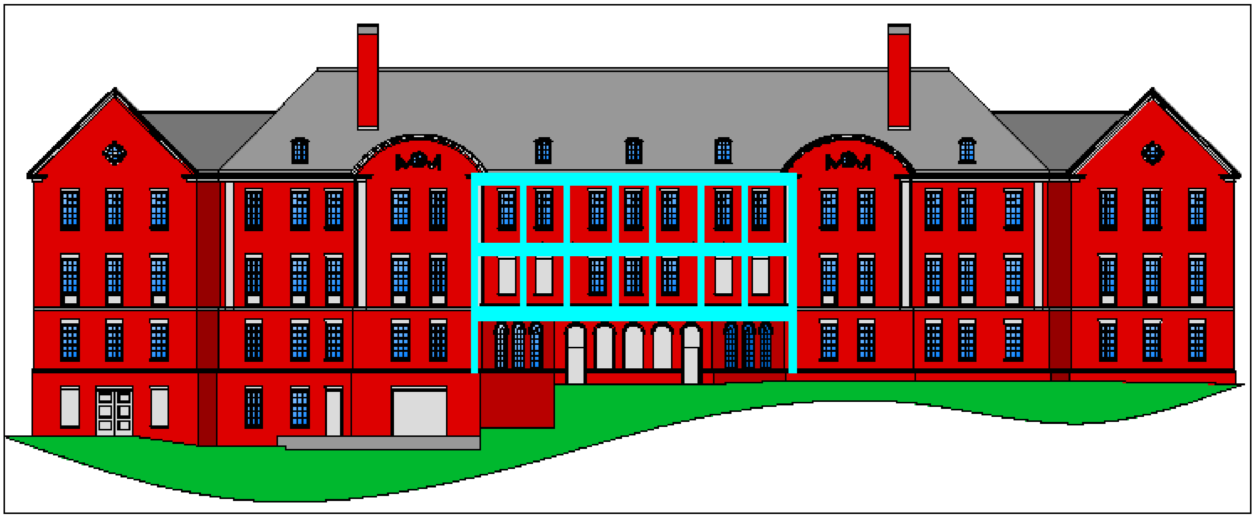

Figure 8.1.1 West Façade with Vierendeel Truss

The long span joist system, as pictured in Figure 8.1.2, also protects the integrity of the façade's architecture. The joists that lie within the façade have the same nominal depth as the girders in the Vierendeel truss. The joist members also have the added advantage of open webs, which create spaces for the four 12-inch web penetrations required in the lowest girder of the truss (see Figure 2.6.1).

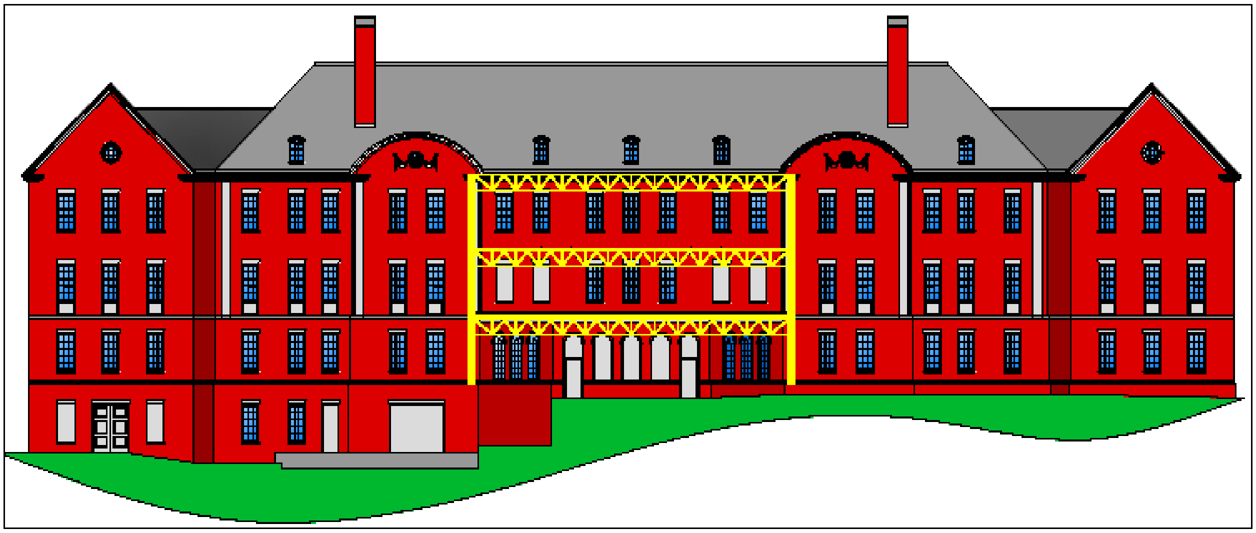

Figure 8.1.2 West Façade with Long Span Joists

8.2 Interior Space – Above Ceiling Assessment

The potential problem with the long span joist system lies within the plenum space above ceiling. The existing system uses W16x31 beams to span the transverse direction from the typical framing at the center of the building to the Vierendeel truss at the exterior. The new system of long span joists has 40LH16 members spanning across the lecture hall on the ground floor and across teaching labs and classrooms on the upper two floors. There is a nominal difference in depth of 24-inches. The rooms are designed with a typical 9-foot ceiling height and a total above ceiling plenum depth of 53-inches. If the ceiling height is to be maintained, there would only be 13-inches for mechanical ductwork in the long span joist system.

The ductwork needed to be investigated in order to properly assess the alternative structural system. If all the ductwork can be reduced to a maximum depth of 10-inches, then the ceiling height would only have to decrease by maximum of 4-inches and the long span joist system could be a viable option. Partial HVAC Ductwork plans provided by EYP are available in Appendix C. Five ducts need to be altered for the long span joist system: a 30x18 return duct on the first floor and two 24x18 supply ducts on each of the two upper floors. Using the design tools in Fundamentals of Thermal-Fluid Sciences by Yunus A. Cengel, I was able find 10-inch ducts that have the same fundamental friction loss. The new duct sizes are listed in Figure 8.2.1. By maintaining the same friction loss, I ensured that only the ducts, and not the mechanical equipment, were resized. If the friction loss was greater for the altered duct, then the fan would use more energy to supply air to the spaces at the prescribed exit rate. However, the newly-sized ducts have a much higher aspect ratio then the existing ducts, which means more sheet metal to enclose and a more expensive duct. The widths of the new ducts are also a cause for concern as the plenum space is going to be very congested with only 17 inches of free space in which to fit numerous utilities. However, the bottom line is that the long span joist system can be made viable with a little extra money and a few changes to the HVAC ductwork.

Friction Factors of Fully Developed Laminar Flow		
w/d	f	F
1	56.92/Re	56.92
2	62.20/Re	62.20
3	68.36/Re	68.36
4	72.92/Re	72.92
6	78.80/Re	78.80
8	82.32/Re	82.32
inf.	96.00/Re	96.00

$F = f \times Re$

$Re = V_m * D_h * v$

$D_h = (2wd)/(w+d)$

Try to keep V_m & v constant.

Find New w-value that Produces Same F-value as Existing Duct.

Duct Size		Aspect Ratio w/d	Hydraulic Diameter, D_h	F
Depth	Width			
18	32	1.78	23.0	1406.3
10	70	7.00	17.5	1409.8
18	24	1.33	20.6	1207.1
10	44	4.40	16.3	1207.5

Figure 8.2.1 Design of Equivalent Flattened Duct Sizes